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Barrage Balloon Skyhook

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Abstract

An experiment was conducted to determine the feasibility of using a large captive balloon to deploy an array of pressure sensors vertically above a large explosion. A British World War-II type barrage balloon was used up to an altitude of 8,600 ft above mean sea level. The payload consisted of a 5-station gage array distributed along the tether. A 5/16-in. diameter stranded fiberglas cable was used for the single tethering line.

As a result of the tests, it is concluded that a distributed payload of up to 750 lb can be deployed in a near vertical and very stable array with a barrage-type balloon up to 10,000 ft mean sea level. The system can be launched and maintained aloft under fairly adverse weather conditions and has significant advantages over other methods of gage positioning, for example, rocket emplacement, in terms of simplicity, reliability, and economy.

1. INTRODUCTION

During the first week of December 1966, the Naval Ordnance Laboratory (NOL) and its contractor, Raven Industries, Inc., conducted a test to determine the feasibility of using a tethered balloon system as a "skyhook." For many years the Laboratory has been concerned with the dearth of experimental pressure-time data acquired at high altitudes in the region directly above large explosions. The balloon skyhook concept was designed for use on large-scale field operations either over water or over land. Large size charges weighing up to hundreds of tons would be detonated, and the balloon-supported tether line would provide a means for positioning pressure transducers at selected levels up to 10,000 ft above mean sea level.

Operations such as envisioned are usually large operations. A number of agencies utilize the operation to obtain data of special interest to them; thus inter-agency or inter-project coordination is required in such mundane things as location of equipment and time for emplacement. Working in the field imposes certain interesting constraints. Weather conditions become important and, particularly for balloon flights, conditions for launching the balloon and flying the balloon must be favorable. For a variety of reasons, "holds" in the over-all operation may be necessary: weather deteriorates, malfunctions occur, someone isn't ready. These facts of life for field operations dictate specific requirements for the balloon system. These requirements can be delineated thus:

The system should be capable of performing as a "skyhook" for the purpose of lofting and accurately placing instrumented payloads weighing up to 750 lb, excluding tether, to an altitude of 10,000 ft above mean sea level.

The system must be capable of accepting a payload which would be distributed from the surface to 10,000 ft, having sensors placed at preselected discrete locations.

The system must be capable of being launched without windbreak or shelter in winds up to 20 knots. It should withstand winds up to 40 knots, when in position, for a minimum of 72 hours with a maximum change in inclination of 20°, with respect to a vertical through the mooring point, from the time mooring is complete until the event being studied takes place.

The system must be capable of satisfactory operation on land or at sea without loss of effectiveness.

2. PRETEST PREPARATIONS

The pretest preparations included such things as the selection of a suitable test vehicle, the design and fabrication of a realistic payload and the selection and preparation of a suitable test site.

2.1 The Balloon

The balloon test vehicle selected was a World War II-type British barrage balloon, Mark 84 (see Figure 1). The inflated balloon is 112 ft long, 40 ft in diameter with an approximate gas volume of 80,000 cu ft, a weight of 1700 lb, and a gross lift of 3900 lb at 10,000 ft. The aerodynamically shaped balloon has a ballonet which is pressurized with ram air and has air-inflatable fins and rudder. It is designed to withstand winds up to 80 knots. The balloon used in this test was manufactured in 1958 and was in excellent condition. requiring only minor repairs of damages incurred in shipping. The only refurbishment effort made was the repainting of the top portion of the gas envelope to minimize helium losses.

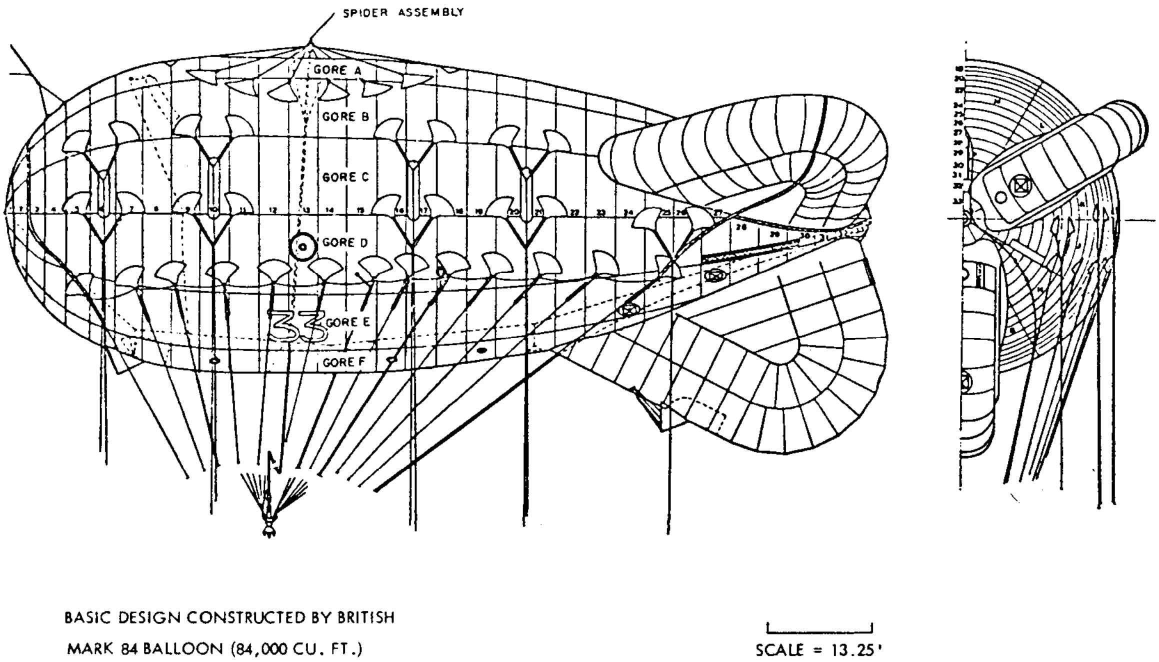

Figure 1. General Arrangement of Balloon

2.2 The Tether

Selection of a tether line for the balloon involved consideration of trade-offs among such factors as strength of lines, total lift capacity of balloon, and cost of line. A complicating factor in tether selection resulted, in that there was some question as to the actual volume (and hence lift capacity) of the balloon. Estimates of volume ranged from 70,000 to 84,000 cu ft.

Two tethering line materials were considered -- steel and Glastran (R) each in two sizes, 1/4 and 5/16-in. diam and 5/16 and 3/8-in. diam, respectively. For the estimated fixed weight of the balloon, rigging and payload (2525 lb), calculations were made for different balloon volumes and the several candidate tether lines to determine the most suitable material.

It was apparent that if the original performance requirements (payload, weight, and altitude) of the system were to be met, the only tether material with a chance for success was the 5/16-in. Glastran; it alone provided the system with an adequate free lift for all conditions considered. Even with this choice of tether material, it appeared chancy whether a successful flight could be obtained with a 70,000 cu ft balloon, since the excess lift available would be only 175 lb.

On the other hand, if the most optimistic volume guess were correct, an 84,000 cu ft balloon would support a 1/4-in. steel tether with an excess lift of 465 lb at the start of the experiment and one could visualize that enough aerodynamic lift would be developed to compensate for relatively large helium losses during the 72-hour flight.

However, the selection of this cable configuration would underscore the importance of another area of uncertainty -- that of the maximum tension which would be developed in the cable during the flight. Hence, the lack of accurate knowledge of the vehicle and its aerodynamic lift capabilities under wind conditions made it prudent to select a tether material with a factor of safety greater than the minimum of 1.4:1.

To complete the discussion, two additional modes of comparison need be mentioned -- one technical and the other economic in nature. The technical point concerns the state-of-the-art in the development and utilization of the two materials. The many years of experience in the design and fabrication of steel cables have yielded a product which is very near the ultimate in its physical properties and highly predictable in its response to applied stresses. In addition, the design of handling equipment has been improved over the years to the point where maximum utilization of the cable is realized. In comparison, the use of fiberglas as the basic material for rope or cable construction is a relatively new concept. While the potential is very high, fabrication techniques are in the infancy of development and usage experience leading to the generation of acceptable handling techniques is negligible.

The economic factor is an important one for this low budget experiment. The cost of fiberglas cable is very nearly ten times the cost of steel cable of the same rated breaking strength.

The choice of tether material was made for an assumed volume of 75,000 cu ft. Table 1 shows the comparison between steel and Glastran cables for this balloon volume. By comparison of the figures on free lift available and the relative strengths of the two cables, the reasons for the selection of the Glastran cable are obvious.

Table 1. Comparison of Steel and Fiberglas Tethers for an Assumed Balloon Volume of 75,000 cu ft

Cable Type	1/4" Diam Steel	5/16" Diam Glastran
Maximum lift available for tether (lb)	1125	1125
Total weight of tether (lb)	1100	700
Net free lift available (lb)	25	425
Rated breaking strength (lb)	7000	10,000
Factor of safety	1.4:1	2.0:1

2.3 The Payload

In the interest of minimizing payload weight, it is most economical to use the balloon tether as a structural member to support the payload in an operation of this nature. Since the aerodynamic drag on the payload and the tether and the nonlinear weight distribution of the payload along the tether would have a major effect on the shape of the catenary the tether assumed, an accurate simulation of the payload with respect to its drag and weight properties has been made. The payload consisted of two major assemblies -- the gage stations and the electrical cable through which would be transmitted the signal to turn the gages on and the signals from the gages to a tape recorder on the surface. The total weight of the payload was 610 lb.

2.4 Test Site

The field test was conducted at the Army airport at Camp Atterbury, Indiana, where there are excellent ground facilities plus restricted air space up to 45,000 ft.

3. THE TEST

3.1 Test Procedure

The test was to be conducted in two phases. The first would consist in inflating and launching the balloon under somewhat ideal surface wind conditions (say winds of from 0 to 5 mph); raising the balloon to altitude, while attaching the payload; and flying the balloon at altitude for 72 hours. It was hoped that for some period during this phase the balloon might experience winds of magnitudes as great as 40 knots. During this flight, position data would be acquired on the balloon and the five gage stations and correlated with available concurrent wind data and lift reduction due to helium loss. From these data, we could then determine the variation in line of sight distance to each gage station from a fixed event point on the surface. The second phase was designed to determine the limitations imposed on the system when the inflation and launching operations were attempted under adverse surface wind conditions. The experimental plan was to stand by until the surface winds reached a velocity of the order of 20 knots and attempt inflation and launching to an altitude of 500 ft in the presence of this high wind environment.

3.2 The Phase I Test

The Phase I test was conducted during the period 2 to 5 December. The first day was expended in laying out the balloon, inspecting for damage, repairing damaged areas, laying on the rigging, inflating and weigh-off. The complete process took 6 hours, 2 hours of which were devoted to inflation. During the morning of the second day, tail ballast was added to increase the angle of attack, and remotely controlled destruct equipment was installed. A second weigh-off was made prior to haul-out to determine the helium leakage rate. The loss was 30 lb for an 18-hour period. Haul-out began at noon, with the payload being added during the process. The total time of the haul-out to 8600 ft msl was 4.5 hours. The tension in the cable (with the balloon at altitude) varied between 1450 and 1600 lb. Since the calculated gross free lift was approximately 900 lb, the aerodynamic lift varied from 450 to 700 lb. The weather forecast for the night of 4 December called for increasing winds and severe icing at the 6000 to 7000-ft level. We decided to pull the balloon down to 4000 ft and moor it at that altitude overnight. At mooring, the tension had reached 2800 lb. At 0500 on 5 December, the tension in the cables had reached 3625 lb. Two hours later, the cable parted due to a sheave failure on the winch. The balloon rose rapidly and burst. While there is no record of the tension which had developed in the cable at the time the winch failed, it is felt that it must have exceeded 4000 lb, since the system had been tested at this tension prior to the launch.

4. DISCUSSION OF RESULTS

4.1 Payload Versus Altitude

The original requirement that the balloon system be capable of suspending a 750-lb distributed payload to an altitude of 10,000 ft was not achieved in the experiment. However, extension of the data acquired allows us to demonstrate the feasibility of achieving such a goal with some minor design changes (see Table 2). The gross weight of the system as it now stands is 3617 lb. If the rigging were redesigned to change the angle of attack, the necessity for the tail ballast would vanish and if one could accept the inherent self-destruction characteristic of the balloon as the only destruct mechanism, the drop weight and remote destruct instrumentation could be removed. Existing heavy steel hardware could be replaced with aluminum hardware and the diffusers could be removed after inflation and prior to haul-out. Thus there would be a net savings of 317 lb, giving a new gross weight of 3280 lb, and, if the gross lift at 10,000 ft is 3900 lb, the free lift available would be 620 lb.

Table 2. Design Comparison of System Gross Weight
(In pounds)

System Gross Weight as Now Designed	
Existing balloon and equipment weight	2097
Proposed payload weight	750
Tether weight for 10,000-ft altitude	770
Gross weight	3617
System Gross Weight Savings by Redesign	
Removal of tail ballast	170
Removal of drop weight	40
Removal of destruct instrumentation	85
Substituting aluminum for steel hardware	30
Removal of diffusers	12
Net savings	337
Existing gross weight	3617
Less weight saved by redesign	337
New gross weight	3280
Gross lift at 10,000 ft msl	3900
Gross weight	3280
Free lift (fully pressurized balloon)	620

Thus, we see that even in the absence of aerodynamic lifting forces (a highly improbable situation) and with a very conservative prediction of helium losses (say 100 lb per day) the system could support the projected payload at the 10,000-ft altitude for several days.

4.2 Position Stability

An extremely important consideration for end-item use is the ability of the system to restrain the migration of the sensing stations to relatively small excursions with respect to an event on the surface under the influence of varying environmental conditions. The premature termination of the test prevented the acquisition of data over the complete wind velocity spectrum desired. However, sufficient information was gathered to establish the feasibility of the technique. Measurements of flying cable catenary, with the attached gage stations, were made using two theodolites. One (theodolite A) was located at 324° -- 6600 ft from the mooring point; and the other (theodolite B) was located at 54° -- 2500 ft from the mooring point. Figures 2 and 3 represent the plots of two typical sets of measurements. Each of these figures is a composite showing two elevations and one plan view. The left-hand elevation is that seen by theodolite A, and the right-hand elevation is that seen by theodolite B. Figure 2 shows the shape of the catenary in a light wind situation and Figure 3 shows the shape of the catenary in a high wind environment. Comparison of these two figures clearly demonstrates the stability of the system relative to the mooring point. In spite of the contrast between wind conditions on 3 and 4 December, the change in line-of-sight distance and the vertical angle from the mooring point to each station is remarkably small. The maximum distance change was one percent and the maximum angular change 2.7°. The balloon stayed well within the 20° vertical angle stipulated in the original requirements.

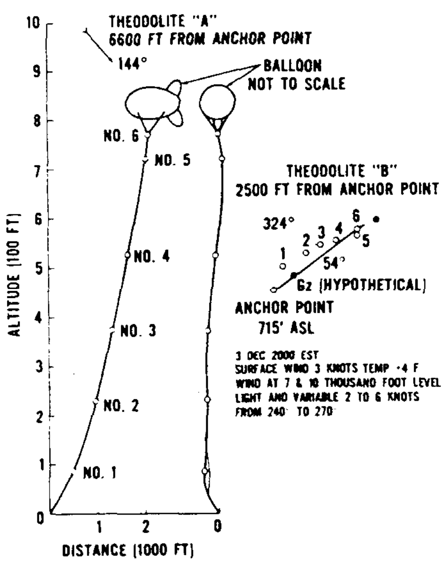

Figure 2. Catenary Shape at 2000 hr, 3 December 1966

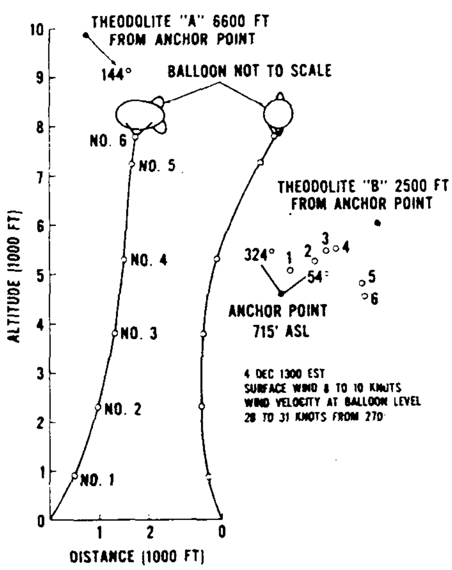

Figure 3. Catenary Shape at 1300 hr, 4 December 1966

This small influence of wind velocity on the off-set of the gage station array from the vertical, that is, from directly over the mooring point, can be used to advantage. For the experiment which we have in mind, it is desirable to make measurements in a small volume of space directly above surface zero, and yet field operational conditions discourage the placing of extraneous material at surface zero. Analysis of the test results show that gage stations can be positioned in a 40° cone above surface zero by placing the mooring point of the balloon line about 500 ft from surface zero in the predicted up-wind direction (see Figure 2). In this way, with reasonable wind predictions and resulting tether line catenary, gages can be positioned with acceptable accuracy in a zone directly above surface zero without compromising the surface zero ambient conditions.

4.3 Launch Under Adverse Wind Conditions

The loss of the balloon during the Phase I test precluded the acquisition of data designed to demonstrate that the system could be launched in the open in winds up to 20 knots. On the basis of experience gained during the Phase I launch where the winds were of the order of 6 knots maximum, it would be impracticable to launch the system as it is now designed, using the same techniques, in a 20-knot wind. However, by modifying the balloon so as to make available points of attachment for the restraining lines which are better suited to controlling the balloon under high wind conditions, redesigning the rigging procedures so as to achieve more localized control of specific balloon areas and, by increasing the rate of fill to reduce the length of the period during which the balloon is most susceptible to destruction, we believe that launches in winds approaching 20 knots would be possible.

4.4 Launch at Sea

While the feasibility of launching the Mark 84 system at sea has not been demonstrated, the experience acquired during the test at Camp Atterbury does lend credence to the practicability of the concept. The small amount of real estate required by the launch crew and the fact that the ship can head with the wind indicate that the system could be launched successfully from an LST. One potential source of trouble peculiar to using the system at sea is the effect of wave action. It is not known if there is sufficient flexibility in all components of the system to absorb the effects resulting in sudden changes in tether tension due to the action of a heavy sea.

4.5 Electrical Charge Buildup

One problem area which was vividly demonstrated in the Atterbury experiment was that of the balloon system acquiring electrical charge resulting in a large potential gradient relative to the ground. Since the tether was a nonconductor, the only conductive path to ground was through the instrument cable which started 500 ft below the balloon at the fifth gage station. The magnitude of the potential was so great by the time haul-out had proceeded to the third gage station (4,000 ft below the balloon) that it was impossible to connect the gages to the instrument cable. While the magnitude of the potential buildup is not known, it was sufficiently large to be hazardous to launch personnel and at the same time create problems in the instrumentation system itself.

4.6 The Winch Failure

As stated earlier, the experiment was brought to a premature conclusion when the tether parted, resulting in the loss of the balloon. The parting of the Glastran tether was the direct result of the failure of one of the two tension sheaves of the winch shock absorbing system. The sheave flange broke off allowing the tether cable to slip off the sheave. When this happened the cable was stressed over a radius much smaller than the 6-in. minimum bending radius prescribed and as a result the cable parted.

5. CONCLUSIONS

5.1 Feasibility Established

From the results of this study we conclude: (a) that it is entirely feasible to use a balloon system of the type investigated in this experiment to deploy an instrument array vertically above and in the vicinity of a large explosion to altitudes up to 10,000 ft msl; (b) that such a system can be launched and maintained aloft under fairly adverse conditions for reasonable periods of time (say 2 to 3 days); (c) that provided with a suitable platform the system can be launched at sea as well as on land; (d) that the system when aloft will maintain the positions of the various gage stations such that there is a high probability of acquiring acceptable data from a large percentage of the stations.

5.2 Experimental Dividends

A much better understanding has been acquired of areas where little or no information was available prior to the study. For example: it has been demonstrated (a) that if the handling equipment is properly designed and careful handling techniques are observed, fiberglas with its attractive strength-to-weight ratio is a suitable tethering material; (b) that properly trained, a crew of 8 to 10 men can inflate and launch the system from an area as small as 70 × 130 ft in 8 to 10 hr; (c) that the stability of the system is much better than originally hoped; and (d) that if one desires to launch the balloon under more adverse surface conditions than those experienced, the balloon hold-down system will have to be modified.